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GODDARD RANGE AND RANGE RATE AND LASER STATION COORDINATES FROM GEOS-II DATA

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GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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by

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ABSTRACT

Dynamic solutions combining optical, laser and Goddard Range and Range-Rate (GRARR) observations of GEOS-II have yielded definitive results for center of mass station coordinates for three laser and four GRARR tracking sites. Comparisons with independent solutions and internal consistency suggest an accuracy of 10 meters or better in most cases. Comparisons of intersite distances on a datum suggest accuracy equal to or better than that usually associated with first order surveys. The outstanding consistency obtained with combinations of optical and scale-providing data suggest that the value of GM (= 3.986013×10^{14} m^3/sec^2) obtained by JPL from deep space tracking is highly accurate.

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GODDARD RANGE AND RANGE RATE AND LASER STATION COORDINATES FROM GEOS-II DATA

1.0 INTRODUCTION

Definitive center of mass coordinates for the Tananarive, Madagascar; Rosman, North Carolina; Fairbanks, Alaska; and Carnarvon, Australia Range and Range-Rate sites, and the Wallops Island, Virginia; Goddard Space Flight Center (GSFC) and Carnarvon Laser sites have been estimated from GEOS-II data. Comparison [1] with our previously obtained optical coordinates indicates a high degree of consistency. Laser range, GRARR range and range rate, and optical data are all consistent; the station positions obtained agree with the optically derived results to 10 meters or better. The GSFC laser position also agrees well with recent SAO estimates [2, 3]. For an example of the precision obtained, the surveyed interstation distance between the Fairbanks GRARR and the Edinburg, Texas MOTS 40 camera agreed with the dynamically obtained value to about nine meters. The chord length is almost 5.4 million meters.

Twenty-nine two-day arcs containing a total of about 11,500 optical observations, and 70 laser and 180 GRARR range and range rate passes were used in the solutions. The data period ran from March, 1968 to May, 1969. Solutions were made using differing weights for the various data types to evaluate the sensitivity of the solutions to data distribution and to reveal inconsistencies.

The estimated coordinates are presented in Table 1. Of special interest are the new center of mass station coordinates for sites in western Australia. The relationship of local to center of mass coordinates can now be used to convert the survey coordinates of the Unified S-Band and C-Band Radar Systems at

Table 1

GRARR and Laser Station Positions

Stations			Latitude*	E. Longitude*	Height* (meters)
Name	Number	Location			
MADGAR	1122	Tananarive, Madagascar (GRARR)	-19° 01′ 14″5	47° 18′ 11″4	1382.
ROSRAN	1126	Rosman, North Carolina (GRARR)	35° 11′ 45″6	277° 07′ 25″8	819.
ULASKR	1128	Fairbanks, Alaska (GRARR)	64° 58′ 19″0	212° 29′ 12″1	340.
CARVON	1152	Carnarvon, Australia (GRARR)	-24° 54′ 11″4	113° 42′ 58″9	1.
GODLAS	7050	Goddard Space Flight Center (LASER)	39° 01′ 14″1	283° 10′ 18″4	3.
WALLAS	7052	Wallops Island, Virginia (LASER)	37° 51′ 36″0	284° 29′ 24″0	-60.
CRMLAS	7054	Carnarvon, Australia (LASER)	-24° 54′ 16″4	113° 42′ 57″9	-5.

*(Coordinates referred to an ellipsoid of flattening 1/298.255 and semi-major axis equal to 6,378,155 meters. These parameters are consistently used throughout the text.)

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Carnarvon to the center of mass system. Prior to our analyses accurate center of mass coordinates were not available for these stations.

Both the 1969 SAO American Geophysical Union (AGU) [2] and 1969 SAO Standard Earth (SE) [3] Gravity models were used. The near identical results obtained indicate that our estimation scheme is relatively insensitive to gravity model error.

These two gravity models produce orbits which differ along track by as much as 40 m [4] at times, but this error was not translated into significantly differing station position estimates for reasons given below.

2.0 STATION POSITION ESTIMATION

The GEOS-II satellite orbital specifications are presented in Table 2. The orbital arcs used were chosen to provide the geometry needed for accurate station estimation. Resonance is a problem [4] for the GEOS satellites, but was dealt with by our use of multiple, short (2 days) arcs.

Our approach to the station estimation problem was dynamical using Cowell's method to solve the equations of motion. The solutions contained a large number of SAO Baker-Nunn observations in addition to the (primarily continental United States) STADAN and SPEOPT optical observations. Because of the large number of electronic compared to optical data points taken per pass, we selected electronic data so that the total per pass was approximately 50.

Based upon our experience [1], we have concluded that the use of two-day arcs provides an accurate means for recovering station parameters. Such orbital arcs are long enough to have a large amount of data, but not so long that error growth becomes excessive.

Table 2

Orbital Elements of GEOS-II

	GEOS-II
Epoch	April 28, 1968
Apogee Height	1569 Kilometers
Perigee Height	1077 Kilometers
Eccentricity	0.03
Inclination	105.8 Degrees
Anomalistic Period	112.1 Minutes

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Most Baker-Nunn station positions were held fixed at their 1969 AGU values [2]. The STADAN and SPEOPT and certain Baker-Nunn optical stations were also held fixed at their GSFC 1970 values [5]. As an internal check, the Madagascar GRARR station coordinates were recovered with and without Tananarive MOTS 40 optical data. Table 3 compares the present solutions with coordinates derived via survey data from our previous optical solutions. The agreement is very good, except for the cases of Alaska and Carnarvon. In these cases the closest optical stations were several thousand kilometers away. The new Alaska and Carnarvon positions are thus important for deriving positions of other stations in these areas for which geodetic-quality/quantity data is not available. Table 3 also shows that our solutions were relatively unaffected by gravity model error. The good results were obtained by having (where possible) passes on all sides of the stations and in opposing directions. Figures 1.1 through 1.7 present the geometry of the passes in the present solutions. The length of the lines indicate the pass lengths. Although in the case of the Goddard and Wallops Lasers the coverage was poor, good results were obtained because the wealth of data from North American Datum (NAD) optical stations prevented large satellite position error over the United States.

Table 4 presents the arcs used in these solutions and the number of observations and passes for each of the stations. These arcs were carefully selected in order to maximize the worldwide optical coverage while at the same time permitting a large number of electronic passes per recovered station.

The validation of the GRARR data presented certain problems. Thanks to the extensive evaluation of the GRARR data by John Berbert of GSFC [6] it was felt

Table 3

Estimated Station Positions, and Derived Positions Based Upon Optical Control Points

Stations	Solution	Latitude	E. Longitude	Height (meters)
MADGAR	derived[1]	-19° 01' 14".8	47° 18' 11".4	1381
(GRARR)	GSFC dynamic	(AGU)[2] 14".5	11".4	1382
		(SE)[3] 14".5	11".3	1382
ROSRAN	derived	35° 11' 45".4	227° 7' 26".0	814
(GRARR)	GSFC dynamic	(AGU) 45".6	25".8	819
		(SE) 45".6	25".8	819
ULASKR	derived	64° 58' 19".3	212° 29' 10".9	333
(GRARR)	GSFC dynamic	(AGU) 19".0	12".1	340
		(SE) 19".0	12".1	340
GODLAS	derived	39° 01' 13".9	283° 10' 18".4	-2
(LASER)	GSFC dynamic	(AGU) 14".1	18".4	3
		(SE) 14".1	18".5	4
	SAO determinations	(AGU) 14".2	18".2	5
		(SE) 14".2	18".3	9
WALLAS	derived	37° 51' 35".7	284° 29' 23".9	-53
(LASER)	GSFC dynamic	(AGU) 36".0	24".0	-60
		(SE) 36".0	24".0	-59
CRMLAS	derived	-24° 54' 16".7	113° 41' 58".2	2
(LASER)	GSFC dynamic	(AGU) 16".4	57".9	-5
		(SE) 16".4	57".8	-3

1. Derived using survey data for the GRARR Station and applying shift from local datum to center of mass system as obtained in previous optical solutions.
2. Dynamically estimated using the SAO AGU 1969 gravity model.
3. Dynamically estimated using the SAO 1969 Standard Earth gravity model.

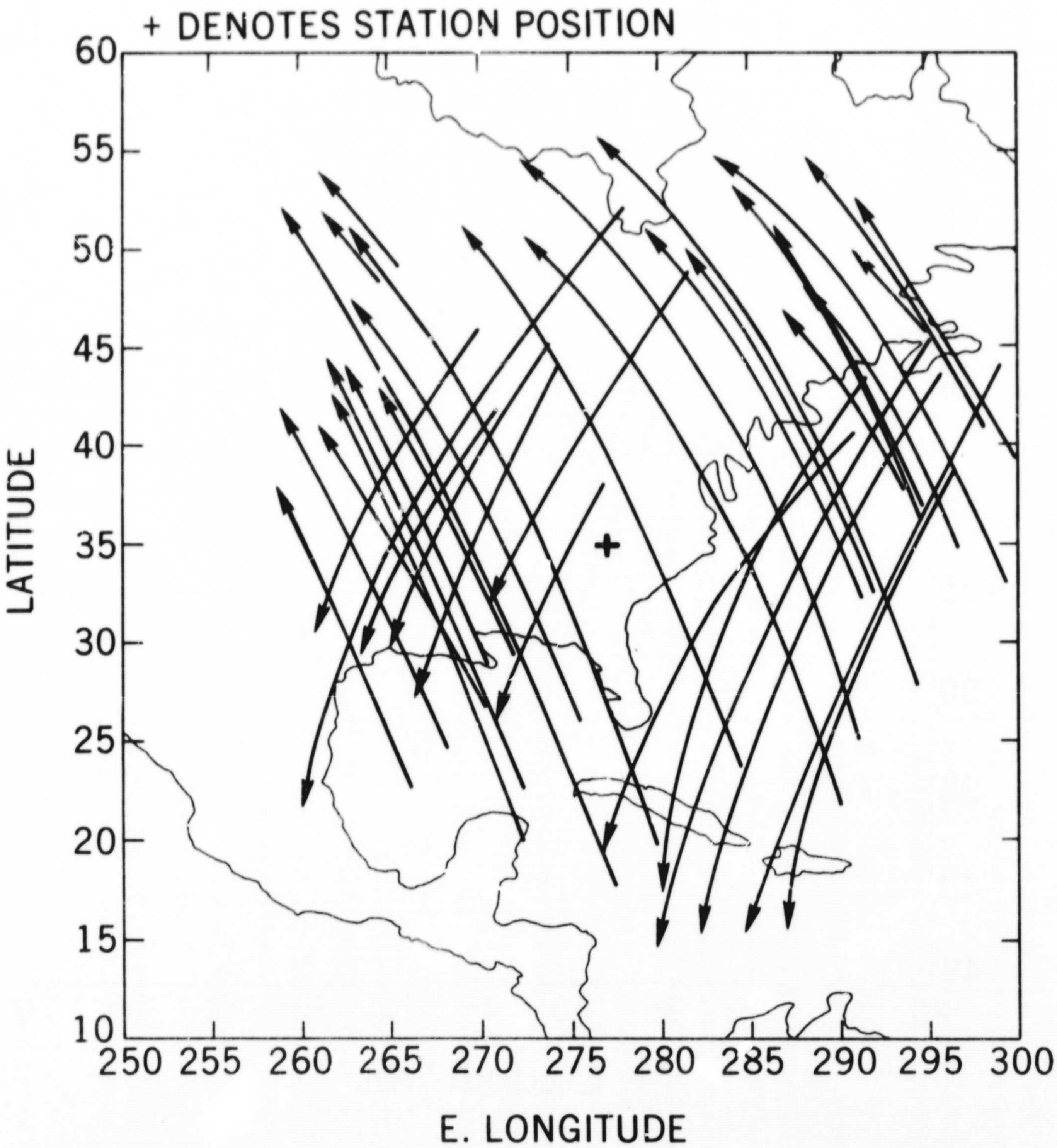

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Figure 1.1. Subsatellite Plots For ROSRAN

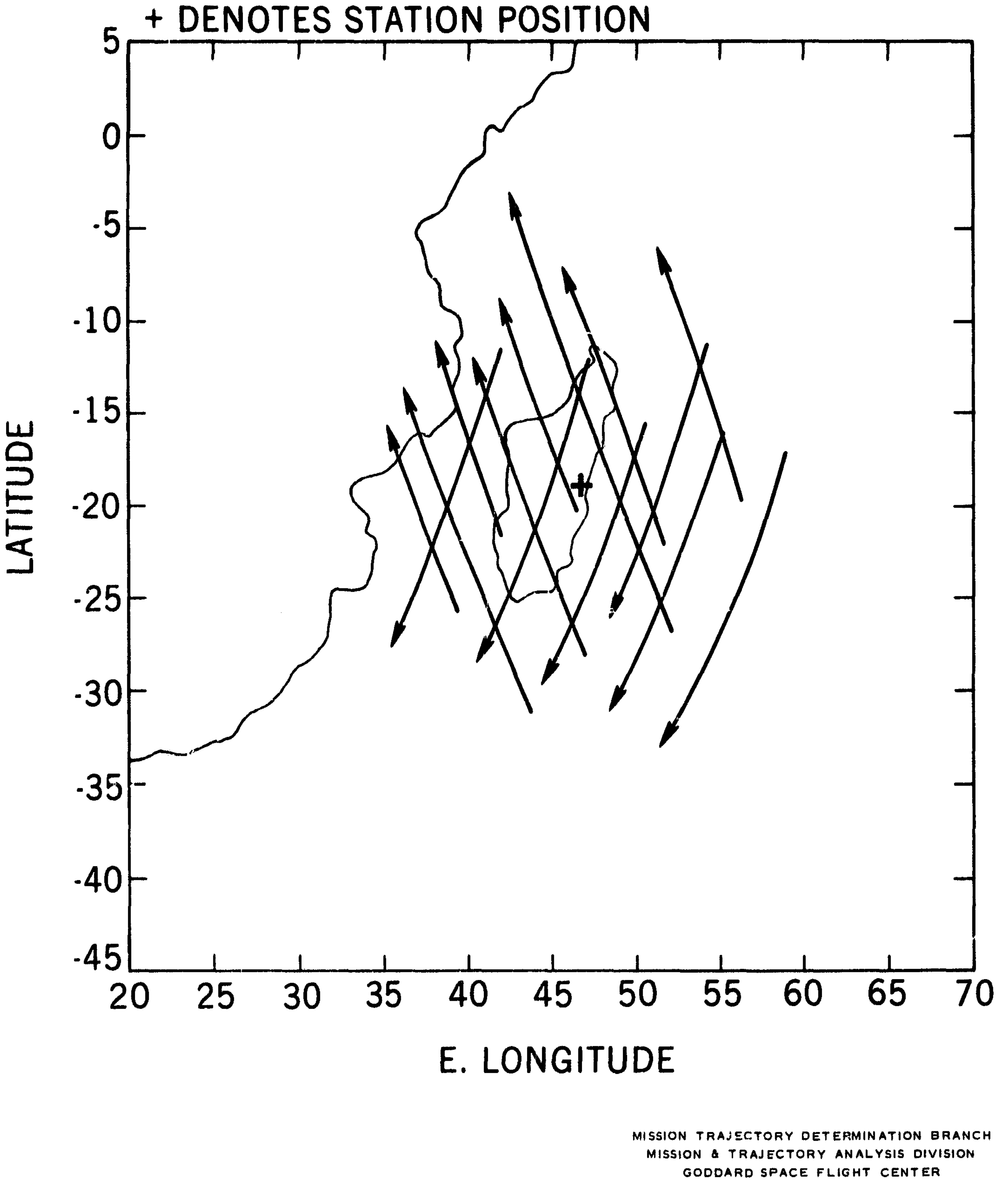

Figure 1.2. Subsatellite Plots For MADGAR

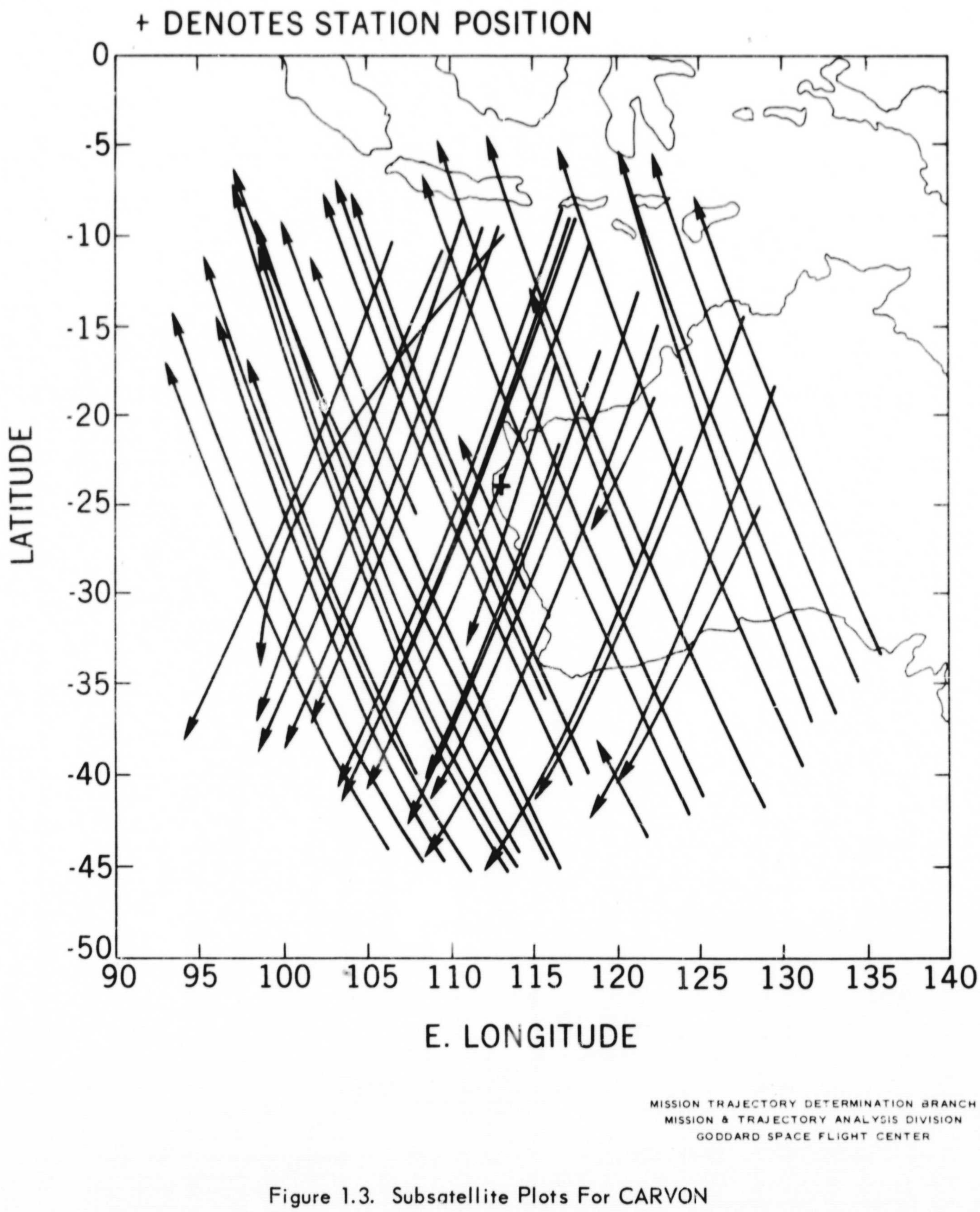

Figure 1.3. Subsatellite Plots For CARVON

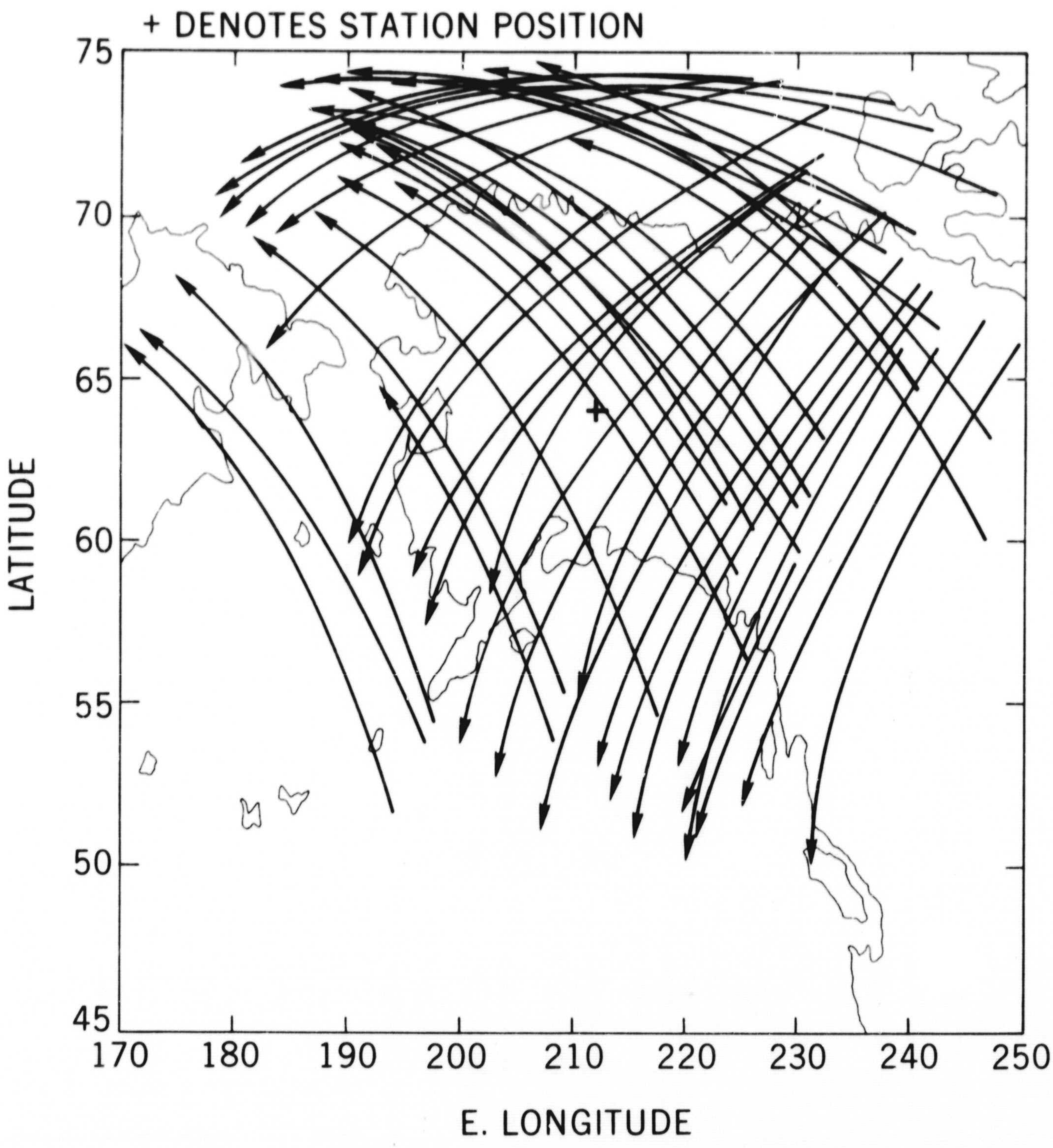

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Figure 1.4. Subsatellite Plots For ULASKR

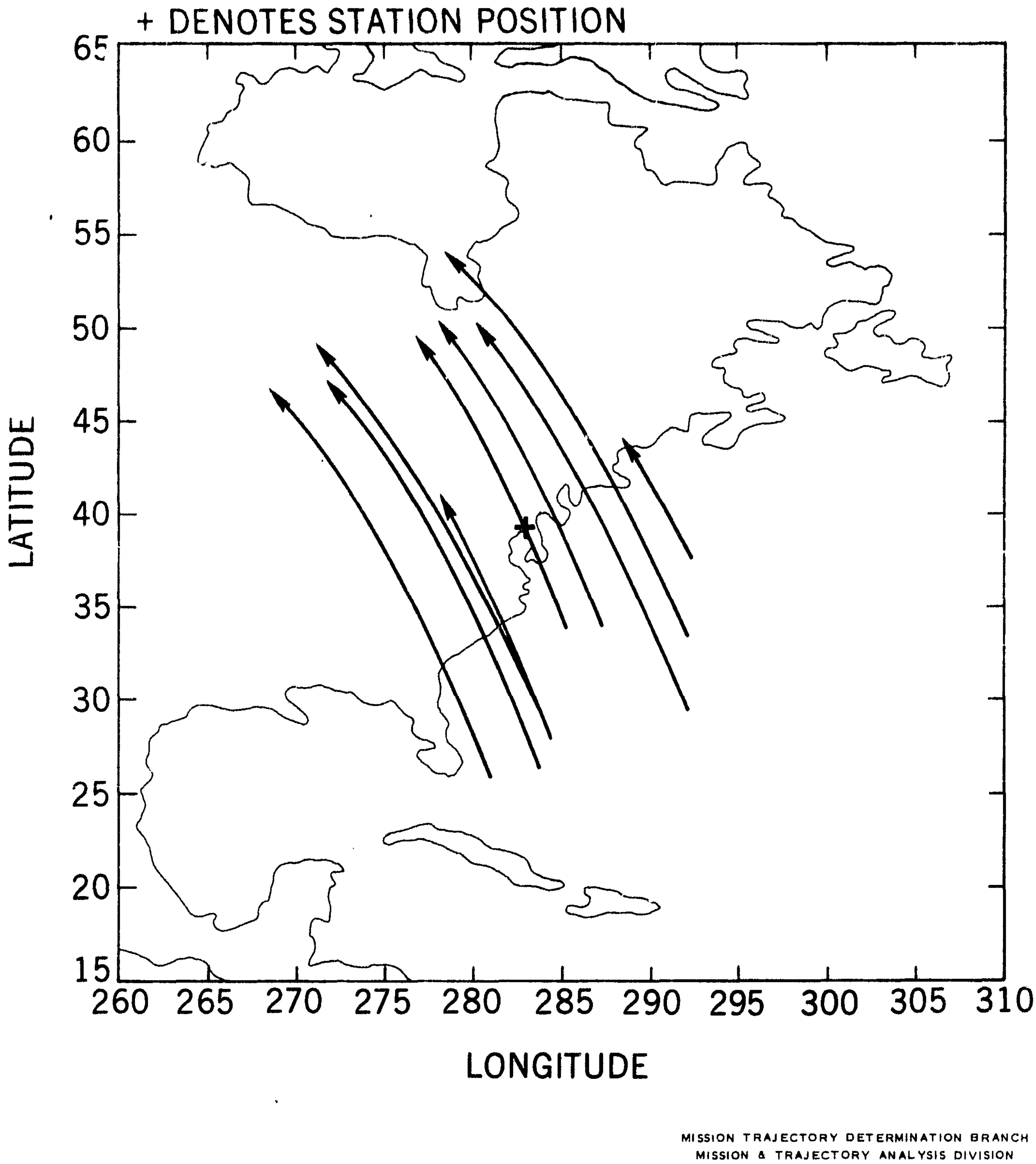

Figure 1.5. Subsatellite Plots For GODLAS

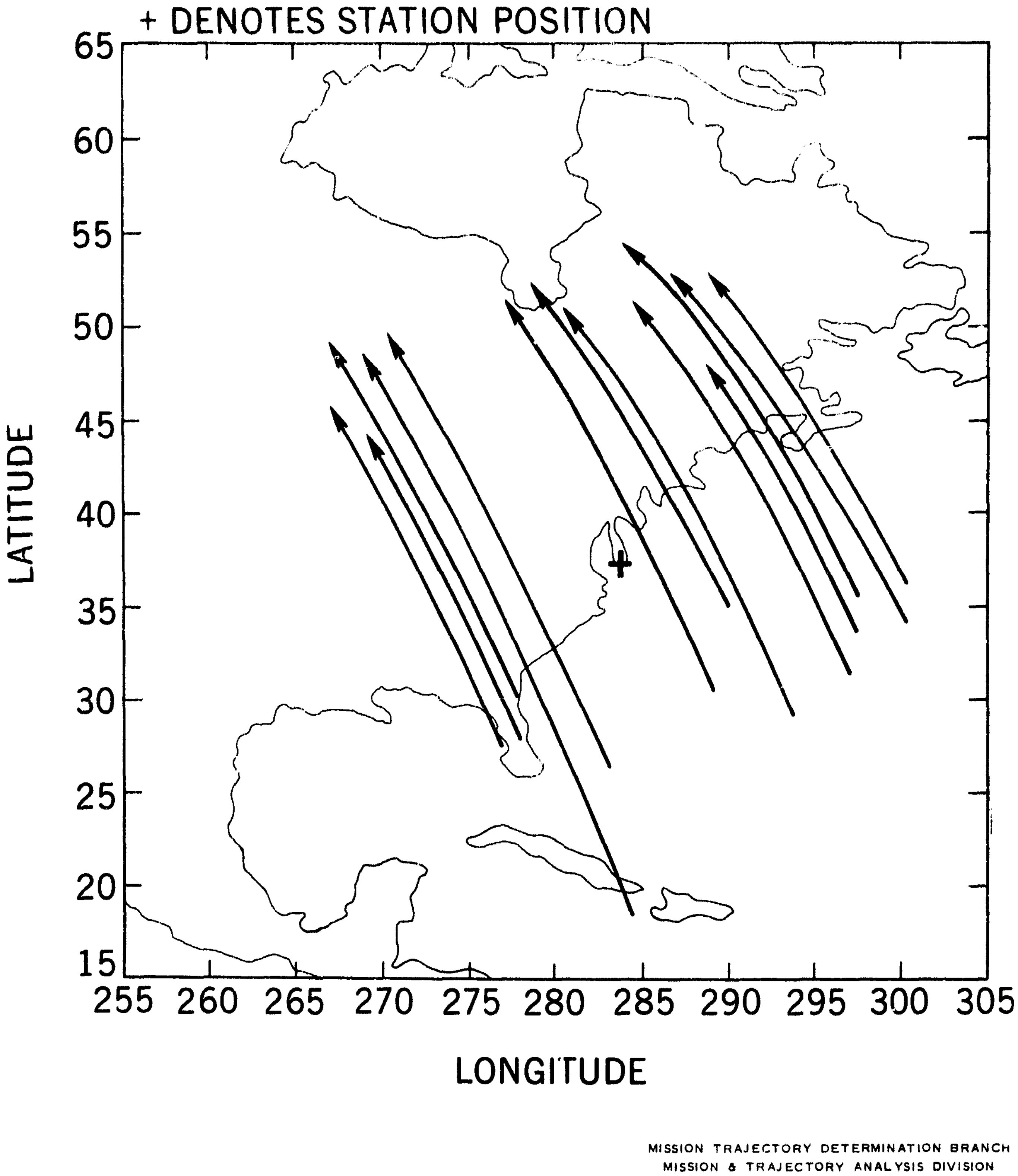

Figure 1.6. Subsatellite Plots For WALLAS

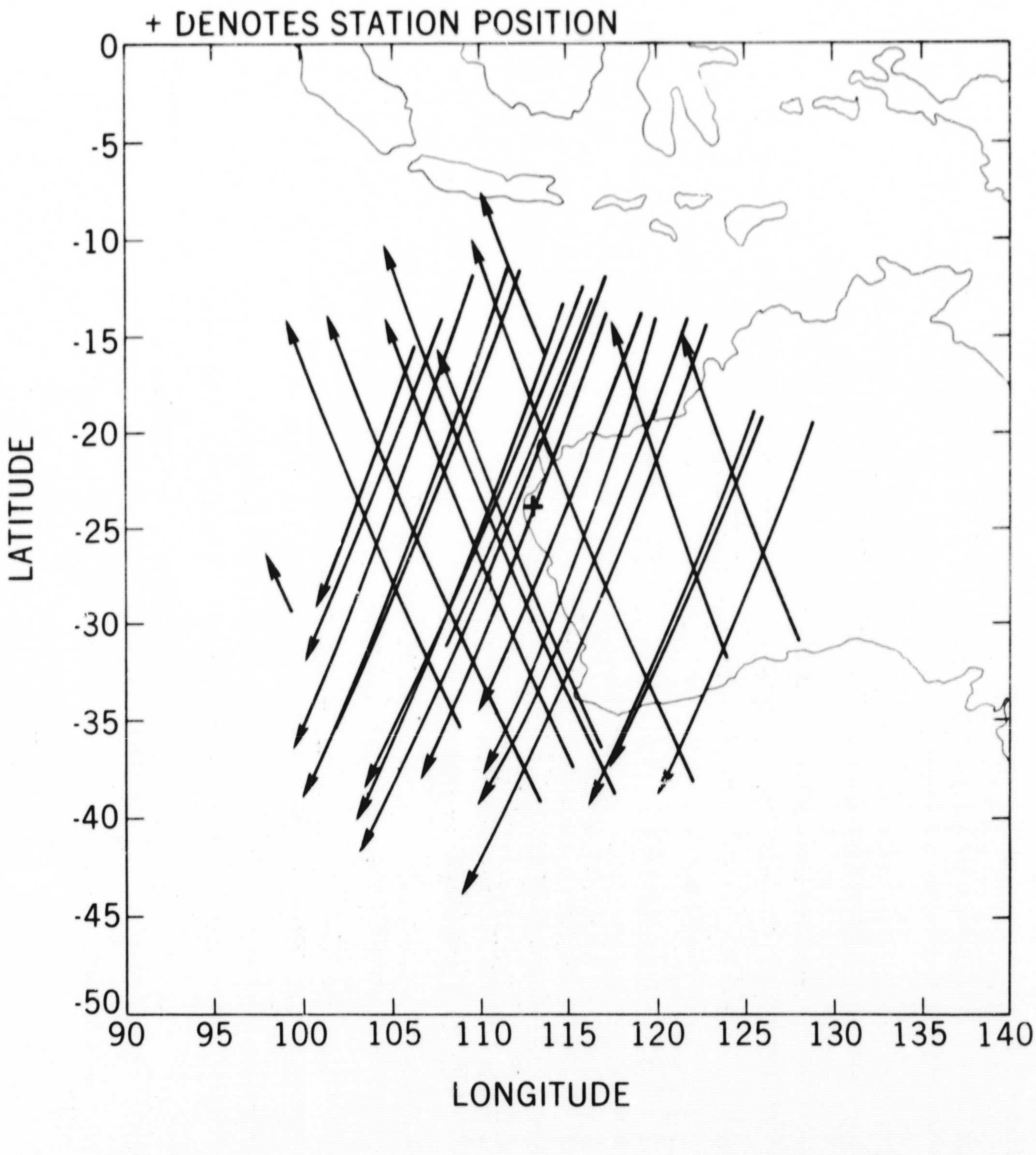

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Figure 1.7. Subsatellite Plots For CRMLAS

Table 4

Arcs Used In Solutions

1968 ARCS

Date	ULASKR No. of Obs. Range	ULASKR No. of Obs. Range Rate	ULASKR No. of Passes	MADGAR No. of Obs. Range	MADGAR No. of Obs. Range Rate	MADGAR No. of Passes	ROSRAN No. of Obs. Range	ROSRAN No. of Obs. Range Rate	ROSRAN No. of Passes	WALLAS No. of Obs. Range	WALLAS No. of Passes	GODLAS No. of Obs. Range	GODLAS No. of Passes	Optical* No. of Obs
1/2-3/68	215	149	3				180	180	3	495	2			314
4/26-27/68	136	84	3				313	313	1	119	1			320
5/7-8/68	172	172	2				102	102	1	480	2			172
5/21-22/68	132	132	2				167	166	4	192	2			351
6/9-10/68	262	262	3				277	277	4					393
6/11-12/68	182	182	3				456	456	5	588	3			828
6/14-15/68	252	252	4				196	197	3					611
6/16-17/68	136	136	2				193	194	3					814
6/21-22/68	271	271	5				263	279	4	122	3			754
6/23-24/68	285	285	5				229	229	4					620
9/24-25/68				111	112	2						69	1	132
9/27-28/68	193	193	3		57	2						38	1	389
10/4-5/68	200	200	3	105	107	2						73	1	286
10/6-7/68	271	271	1	186	189	4								309
10/8-9/68	67	67	1	177	188	4						318	2	507
10/21-22/68	132	132	2									312	2	445
10/23-24/68	202	202	3									437	2	346
TOTALS	3108	2990	48	579	653	14	2376	2393	34	2596	13	1217	9	7821

1969 ARCS

Date	ULASKR* No. of Obs. Range	ULASKR* No. of Obs. Range Rate	ULASKR* No. of Passes	CARVON No. of Obs. Range	CARVON No. of Obs. Range Rate	CARVON No. of Passes	CRMLAS No. of Obs. Range	CRMLAS No. of Passes	GODLAS* No. of Obs. Range	GODLAS* No. of Passes	Optical* No. of Obs.
3/2-3/69	127	127	5	158	158	4	99	2	64	1	150
3/5-6/69	124	124	3	92	129	2	227	3	366	4	360
3/11-12/69	99	99	3	232	232	4	190	3	105	2	474
3/13-14/69	150	150	3	314	379	6	199	3	32	1	295
3/17-18/69	196	196	5	232	237	5	214	4	234	3	224
3/29-30/69	92	92	5	170	170	5					225
3/31-4/1/69	164	163	4	192	206	1	101	2			234
4/8-9/69	75	75	2	167	176	4	146	2	94	3	386
4/10-11/69	172	172	5	90	143	2	321	4	73	1	248
4/14-15/69	123	123	3	99	125	3	271	4			230
4/24-25/69	199	199	5	150	179	3	251	2	159	1	452
5/5-6/69	163	163	4	219	280	4	216	4			544
TOTALS	1684	1683	47	2115	2414	43	2235	35	1127	16	3822

*Station coordinates held fixed.

SUMMARY

GRARR	No. of Obs.
range	9862
range rate	10133
number of passes	186
Laser	
range	7205
number of passes	71
Optical	11643
Total	38843

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that the Rosman, Alaska and Madagascar data sets during 1968 (solution 1) were relatively free of significant biases compared to the noise level, except for a four meter bias due to survey error to the ranging target at Rosman. The Carnarvon GRARR which was also tracking GEOS-II at this time was found to have significant hardware problems which prohibited its inclusion in our first solution. The later 1969 Carnarvon GRARR data set (solution 2) also seemed to have significant range biases when compared to simultaneous bias-free Carnarvon laser passes, indicating that certain problems persisted within this GRARR system throughout the period of interest in 1969. Table 5 presents the estimated range biases for the Carnarvon radar. Berbert's biases were determined by analysis of GRARR residuals based upon laser short arc reference orbits. Our long arc solutions were run with the laser and GRARR sites both held constrained and allowed to adjust independently. In the constrained solution both stations must adjust together by the same amount.

Along with the station coordinates, range biases were also estimated simultaneously with both loose (100 meters) and tight (4 meters) a priori sigmas on the range biases in our solutions. As can be seen from the estimated range bias values, the long arc solutions gave good agreement with the bias values obtained from short arc solutions. In the constrained solutions the agreement was five meters or better in thirteen out of seventeen passes of data. This is good since we were solving not only for a range bias at Carnarvon but also the station coordinates as well. Thus, given the variation in the biases between the independent and constrained solutions and the erratic nature of the magnitude of the biases, it was felt that the Carnarvon GRARR station coordinates could not be satisfactorily recovered independently of the laser-GRARR interstation distance.

Table 5
Estimated Carnarvon Range Biases for
Simultaneous GRARR and Laser Passes — Meters

1969

Data	Berbert Solution	a priori σ = 4m		a priori σ = 100m	
		Constrained	Independent	Constrained	Independent
April 8-9	-10.3	2.5	-1.9	2.2	-6.6
	-12.9	-7.3	4.8	-9.0	3.0
April 10-11	-8.1	-6.3	4.9	-7.0	2.6
April 24-25	0.6	2.5	6.0	2.5	2.5
March 2-3	-9.9	-16.4	-9.0	-18.0	-13.2
	-1.3	-0.5	11.0	-1.3	9.6
March 5-6	-3.7	-6.0	-6.6	-6.4	-10.9
March 11-12	0.0	2.5	4.9	2.2	0.8
	-11.4	-6.8	-0.2	-8.2	-4.1
	-15.8	-11.2	-8.0	-12.5	-12.8
March 13-14	-4.8	-4.2	-5.2	-5.1	-10.1
	-7.1	-7.6	2.8	-8.6	0.3
	-12.9	-15.5	-20.0	-17.4	-26.0
March 17-18	-1.5	-6.0	-1.7	-7.0	-6.1
	-5.0	3.7	11.7	3.6	9.3
	-4.7	-2.8	-1.6	-2.9	-5.6
	0.6	2.6	7.1	2.6	3.8

Table 6

Estimated Carnarvon Laser Station Coordinates

Solution Number	Latitude (N)	E. Longitude	Ellipsoidal Height (m)
1	-24° 54' 16″.4	113° 42' 57″.8	-5.
2	16″.5	57″.9	-4.
3	16″.4	57″.9	-5.
4	16″.3	57″.8	-5.
5	16″.5	58″.0	-7.

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Therefore the final estimated laser-GRARR station coordinates were obtained constraining the laser and GRARR interstation distance. The final Carnarvon laser/GRARR coordinates selected are very satisfactory as can be seen in Table 6. This table gives the laser position:

1 – when estimated independently of the GRARR position,

2 – when estimated from an independent optical/laser-only solution,

3 – when estimated constrained to the GRARR position and solving for a GRARR range bias,

4 – when estimated constrained to the GRARR site using range rate only, and finally

5 – estimated from laser/optical solution with the laser weight being 1/25 of the nominal value of (6 meter)$^{-2}$.

The weight normally given to the laser range data was (6 meters)$^{-2}$. Of course the laser data is much more accurate than this. We obtain fits of 2-3 meters (rms) on a routine basis for orbital arcs of 1 to 3 days. The large nominal laser weight was chosen to ensure significant weight for the optical data. As seen in Table 6, the agreement of solutions is highly satisfactory. Due to the GRARR range biases at Carnarvon previously noted, solution 3 was adopted. The surveyed distance between the Carnarvon laser and GRARR sites should be of extremely high accuracy since they are only about 150 meters apart. Thus, we did not feel that this constraint adversely affected the accuracy of our recovered positions. Table 7 gives the final positions adopted.

Table 7
Carnarvon Station Positions in an Interstation Constrained Optical/GRARR/Laser Solution

Station	Latitude (N)	E. Longitude	Ellipsoidal Height (m)
Carnarvon (LASER)	-24° 54' 16.″4	113° 42' 57.″9	-5.
Carnarvon (GRARR)	-24° 54' 11.″4	113° 42' 58.″9	1.
Carnarvon (Optical)	-24. 58' 23.″4	113° 43' 15.″6	-14.

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Survey data have also been used to provide an important check on accuracy. Tables 8 and 9 present the difference in the surveyed and dynamically recovered interstation chord distances for our dynamically recovered positions on the North American and Australian National Datums. The accuracy of the local surveys is also given. Most of the optical sites on the NAD are of first order accuracy.

On the North American Datum the GRARR and laser intersite distances are in good agreement with the results for previously derived optical stations. The chord length differences in Table 8 indicate that the satellite derived chords are longer than the local survey chords by approximately a few parts per million. The chords to Alaska indicate approximately the same scale change but in the opposite direction. This is not unexpected since the Alaska Station is on a third order survey and ties to the origin of the North American Datum (Meades Ranch, Kansas) are possibly in error. It is interesting to note that in Table 9 for the Australian Datum, the satellite derived chords are also greater in length than the survey chords.

3.0 CONCLUSIONS

It is apparent that our new GRARR and Laser station positions are of comparable accuracy to our previous optical station coordinate solutions. The close agreement of surveyed and satellite-derived intersite distances on the NAD indicates the strength and insensitivity to model errors of our method of station recovery. A consistent agreement with surveyed values of well under ten meters, and ten to fifteen meter agreement to Fairbanks from the Continental United States (with chords almost equalling an earth radius), has been obtained. Thus the GRARR

Table 8

Differences in the Inter-site Distances for First Order Surveyed Positions and Electronic Instruments on the NAD (meters)

[Survey-Satellite]

	1BPOIN*	1MOJAV*	1GFORK*	1ROSMA*	1EDINB*	1COLBA*	1DENVR*	1JUM40[4]	1JAMAC[1]	1PURIO[2]	GODLAS[4]	WALLAS*	ULASKR[3]
1MOJAV	-0.3												
1GFORK	1.1	-8.9											
1ROSMA	1.7	-1.3	-1.5										
1EDINB	-1.7	-2.5	-12.7	-2.2									
1COLBA	3.8	-2.2	-5.3	-0.2	-5.8								
1DENVR	1.7	-1.9	-4.9	-8.1	-8.1	-1.6							
1JUM40	-3.9	-7.4	-10.4	-3.5	-5.4	-6.1	-8.9						
1JAMAC	-1.8	-2.1	-1.4	-2.0	-1.1	-0.7	-1.0	4.1					
1PURIO	-1.9	3.2	0.1	1.1	5.2	3.5	1.7	7.9	8.7				
GODLAS	-5.7	4.4	1.0	-4.1	-7.8	0.2	-1.5	-9.6	-5.8	-5.1			
WALLAS	0.5	-0.1	6.0	-4.7	-7.3	2.5	1.9	-12.7	-8.6	-7.3	3.7		
ULASKR	10.0	10.7	17.3	11.3	8.8	13.5	18.2	4.1	11.3	12.3	10.3	19.5	
ROSRAN	1.7	2.3	2.1	3.4	-2.2	-5.9	-3.4	-10.8	-5.9	-3.8	-3.9	-6.1	16.0

*First order survey

[1]First order independent surveys transformed to the NAD

[2]Second order survey

[3]Third order survey

[4]High precision traverse survey

1MOJAV	Goldstone, Cal.	MOTS Camera
1GFORK	Grand Forks, Minn.	MOTS Camera
1ROSMA	Rosman, N.C.	MOTS Camera
1EDINB	Edinburg, Texas	MOTS Camera
1COLBA	Columbia, Mo.	MOTS Camera
1DENVR	Denver, Colorado	MOTS Camera
1JUM40	Jupiter, Florida	MOTS Camera
1JAMAC	Jamaica	MOTS Camera
1PURIO	Puerto Rico	MOTS Camera
1BPOIN	Blossom Point, Md.	MOTS Camera
GODLAS	Greenbelt, Md.	NASA Laser
WALLAS	Wallops Island, Va.	NASA Laser
ULASKR	Fairbanks, Alaska	GRARR
ROSRAN	Rosman, N.C.	GRARR

Table 9

Comparison of Satellite-Derived and Surveyed Intersite Distances for Australia (meters)

	1ORORL[2]	CRMLAS	1CARVN	CARVON	100MER
CRMLAS[3]	-16.5				
1CARVN[3]	-16.5	0.0			
CARVON[3]	-16.5	0.0	0.0		
1OOMER*	-8.3	-7.5	-7.5	-7.5	
AUSBAK*	-8.3	-7.5	-7.5	-7.5	0.0

(Survey-Satellite)

*First order survey

[2]Second order survey

[3]High precision traverse survey

Constrained in Dynamic Solution	CRMLAS	Carnarvon	Laser
	1CARVN		MOTS Camera
	CARVON		GRARR
Constrained in Dynamic Solution	AUSBAK	Woomera	Baker Nunn
	1OOMER		MOTS Camera
	1ORORL	Orroral	MOTS Camera

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system is a geodetic-quality instrument. The overall RMS of fit in our solutions was 10 m for GRARR range and 7 cm/sec for range rate.

It is felt that this work can only be substantially improved upon if there is further improvement in gravity models. But perhaps as important, we have shown that satellite geodesy can provide accuracy comparable to that of classical methods.

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